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Eye Metrics: An Alternative Vigilance Detector

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Interim Report

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14. ABSTRACT

Many occupational environments require sustained attention or vigilance for long periods of time. Air traffic controllers, cyber operators, TSA inspectors, unmanned aerial systems operators, and satellite imagery analysts encounter lapses in attention due to the sometimes boring and monotonous nature of these tasks. Mistakes in these environments can have devastating consequences. Currently, there is no tool to measure operator performance in these environments and the lapse usually is noticed only after a mistake is made. The purpose of this study was to determine the possible use of an eye-tracker to detect changes in vigilance performance. The results indicate that these oculometrics could be used to detect changes in vigilance. Future research is needed to assess the real-time effects of these oculometrics on vigilance performance, especially in a real-world setting.

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PREFACE

The work covered in the following report was completed with financial support from the Eye-Com, Corp. The work covered in this report began in December of 2011 and was completed in May of 2012. It includes a summary of a research study designed to examine the relationship of various oculometrics with objective performance during a 40-minute vigilance task. Ultimately, the goal was to find an alternative physiologic metric capable of detecting changes in vigilance performance in military aviation settings.

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SUMMARY

Many occupational environments require sustained attention or vigilance for long periods of time. Air traffic controllers, cyber operators, TSA inspectors, unmanned aerial systems operators, and satellite imagery analysts encounter lapses in attention due to the sometimes boring and monotonous nature of these tasks. Mistakes in these environments can have devastating consequences. Currently, there is no tool to measure operator performance in these environments and the lapse usually is noticed only after a mistake is made. The purpose of this study was to determine the possible use of an eye-tracker to detect changes in vigilance performance. Twenty participants volunteered to participate in this study. Each participant performed a 40-minute vigilance task while wearing an eye-tracker on each of four separate days. Blink frequency, blink duration, PERCLOS, pupil diameter, pupil eccentricity, pupil velocity, and signal detection all had a significant change over time ($p<.05$) during the vigilance task. The results indicate that these oculometrics could be used to detect changes in vigilance. Future research is needed to assess the real-time effects of these oculometrics on vigilance performance, especially in a real-world setting. The use of an eye-tracker in an operational environment to detect changes in sustained attention would allow preventative measures to be employed, perhaps by using a perceptual warning system or augmenting human cognition through non-invasive brain stimulation techniques when vigilance declines.

1.0   INTRODUCTION

Sustained attention and vigilance are important issues in today's military operational environment. The widespread use of unmanned aerial systems and increased automation throughout the military environment has led to a need of staying vigilant for long periods of time in static environments. It is well established in the cognitive performance literature that operator performance on tasks requiring sustained attention or vigilance degrades with time; this is known as the "vigilance decrement" (Hitchcock, Warm, Matthews, Dember, Shear, Tripp, Mayleben, & Parasuraman, 2003). During the vigilance decrement, critical errors are made that can have severe or even deadly consequences in these environments (Hawley, 2006). This leads to an increasing need to employ an unobtrusive way to monitor operator vigilance in these settings.

These sometimes devastating lapses in attention are possibly due to the monotonous and sometimes boring nature of these careers (Frankmann & Adams, 1962; Nachreiner & Hanecke, 1992). Various eye metrics have long been associated with arousal levels; therefore, we hypothesize that with the use of a wearable eye-tracking system we may be able to find some oculometrics that correlate with decreases in vigilance performance. In fact, the use of eye tracking technology is employed regularly in the trucking industry to monitor driver arousal because performance becomes less consistent and vigilance deteriorates as a person's sleepiness increases (Dinges, 1990). Several researchers have found that eye tracking technologies can detect fatigue, boredom, and lapses in attention (Dinges, Mallis, Maislin, & Powell, 1998; Russo et al., 1999). Specifically, reduced alertness has been found when eye blinks are longer in duration (Stern, 1999). Another metric that provides alertness information, especially in the trucking industry, is PERCLOS (percentage of eye closure). In fact, PERCLOS is the most widely used measure of real-time alertness in this industry (Dinges & Grace, 1998; Mallis et al., 1999). However, these findings are the result of studies on sleep-deprived participants who are not tested on vigilance tasks.

While research on eye tracking is not as extensive as in the fatigue literature, studies using laboratory vigilance tasks have found some promising results using oculometrics to detect attentional levels. Several studies have indicated that eye gaze is necessary for attention (Blake & Sekuler, 2006; Kramer & McCarley, 2003; Palmer, 1999); therefore, eye movements may be closely related to our attentional levels. For example, some have found that participants not sleep deprived who are placed in a well-lit room but asked to do a boring repetitive task, similar to our task, will mimic the pupil dilations of a sleep deprived individual placed in a dark room (Nishiyama, Tanida, Kusumi, & Hirata, 2007; Warga, Ludtke, Wilhelm, &Wilhelm, 2009). In both instances the pupils dilate initially before becoming miotic (Lowenstein, Feinberg, & Lowenfeld, 1963; Ludtke et al., 1998). Beatty (1982) tested this finding with an auditory vigilance task and found that pupil diameter decreased as a function of time-on-task. In a previous study we found that the oculometrics of blink duration, blink frequency, PERCLOS, pupil diameter, pupil velocity, and pupil eccentricity could be indicators of vigilance task performance (McIntire, McKinley, Goodyear, Merrit, Griffin, McIntire, & Bridges, 2011). These various findings coupled with the extensive amount of research with sleep deprived individuals lead us to believe that oculometrics may provide a reliable method for assessing operator vigilance. In this study we will attempt to replicate our previous findings using a more real-world relevant task in order to determine if the similar results can still be found operationally.

Another aspect of our study employed the use of the Five Factor Model (FFM) personality inventory. Previous research has found that higher Neuroticism and lower Extraversion are predictive of work-related fatigue (e.g., Bohle & Tilley, 1993; May & Kline, 1988). DeVries & Van Heck (2002) found that high scores on Openness and Neuroticism, and low scores on Extraversion and Conscientiousness, predicted self-rated levels of workplace fatigue. No effect of Agreeableness was found. Incidentally, in terms of demographic characteristics, DeVries & Van Heck (2002) also found that women had higher subjective experiences of fatigue, in support of previous research. Studies have also found that Extraversion scores on the FFM can be correlated with cerebral blood flow (Mathew, Weinman, & Barr, 1984). Specifically, cerebral blood flow negatively correlated with a high Extraversion measure, which suggests somewhat indirectly that Introverts are less susceptible to lapses of attention since right cerebral blood flow velocity is related to vigilance performance (Hitchcock et al., 2003; Warm, Matthews, & Parasuraman, 2009; and Hollander, Warm, Matthews, Dember, Parasuraman, Hitchcock, Beam, & Tripp, 2002). Our hypothesis is that there may be some FFM measures or demographic characteristics related to vigilance performance, which may be useful for operator selection purposes.

2.0   METHOD, ASSUMPTION AND PROCEDURES

2.1   Participants

A total of 20 participants (15 male, 5 female) completed this study. Male and female civilian and active duty participants between the ages of 21-41 years with a mean age of 26.1 years participated in this study. Participants were compensated $10/hr for their time. Participants were not included in this study if they required eyeglasses for vision correction because the eye-tracker was mounted on eyeglass frames. The use of contact lenses was allowed for inclusion in the study.

2.2   Equipment

2.2.1   Eye-Tracker

Each participant was required to wear the Eye-Com (Reno, NV) alertness monitoring device Figure 1) during the vigilance task which was repeated across four test sessions, each on different days. The device consisted of two infrared (IR)-sensitive cameras and a linear array of IR-illuminating light emitting diodes (LEDs) mounted on a set of eyeglass frames. The wavelength of the LEDs was 840 nm. The cameras were angled upward toward the eyes and extracted real-time pupil diameter, eye-lid movement, and eye-ball movement. The software recorded a variety of measurements including eye-blink duration, eye-blink frequency, eye-blink velocity, percentage of time the eyes are closed (PERCLOS), and pupil size. The sampling frequency of this device's data recording was 30 frames per second. The tracker monitored blind duration and frequency by tracking the occlusion of the pupil. When 85% of the pupil was occluded by the eyelid the eyes were considered closed for that particular frame. To be considered a "blink" for our analysis the pupil had to be occluded for at least 3 frames because median blink rates for alert individuals usually fall between 130-170 milliseconds (Schleicher, Galley, Briest, & Galley, 2008). If there were less than 3 frames in a row that indicated the eyes were closed it was just considered a bad data point where the tracker lost the pupil momentarily.

PERCLOS is a metric that is calculated by the eye-tracker. PERCLOS was calculated by measuring the proportion of the pupil that is occluded by the upper eyelid. Therefore, PERCLOS is the proportional amount of time when 80% of the pupil is occluded by the eyelid in a 1 minute time frame. Pupil velocity is calculated by tracking how far the pupil moved in a single frame by the location of the pupil on the previous frame. Pupil eccentricity is the extent to which the shape of the pupil deviated from being circular. The shape changes to more elliptical due to occlusion from the eyelid. Therefore, this metric is more a function of the camera losing the pupil than a physiological change in shape. However, it can still provide valuable information about attention if it also reflects information about the eyelid and blinking.

Figure 1. Eye-Com Eye Tracker

2.2.2 Personality Inventory and Demographic Questionnaire

Participants were given a short personality inventory to fill out on their first day. The personality inventory given was the NEO-FFI, which is a shortened version of the Five Factor Model (FFM) (Costa & McCrae, 1992). The "Big Five" personality factors are Extraversion, Agreeableness, Conscientiousness, Neuroticism, and Openness.

2.2.3 Vigilance Task

Participants performed a 40-minute vigilance task that was designed to simulate a cyber defense operator's task. The Cyber Defense Task (CDT) was developed by University of Dayton Research Institute (UDRI) to simulate tasks representative of those found in Cyber Defense Operations. The task is comprised of two components that run simultaneously. The first is a textual component where the participant was asked to monitor and respond to the presence of a suspicious internet protocol (IP) address and port combination entering the network. The second component is a graphics task where the participant was asked to monitor and respond to a dangerous increase in overall traffic within the network (Figure 2). The participant was asked to

memorize specific IP addresses before beginning the task. These IP addresses were suspicious and once they were recognized the participant had to notify a boss of their presence by pressing a key on the keyboard. In addition, the participant also had to press a key when the IP traffic exceeded a predefined limit. This was the graphics portion of the task. Both the textual and graphical task had a critical signal event rate of 5%. At the top of the display there were also three distracter graphs. Participants were not required to take any action on these static images. Performance efficiency was assessed in terms of the percentage of correct signals detected (percent hits). This variable was calculated every 10 minutes over the continuous 40 minute period. Measuring over 10-minute epochs was conducted because the critical signals were designed to appear at random from one trial to the next, but at a specific event rate within 10 minute segments of trials (5%). A new stimulus was displayed every 2000 msec for the graphical portion of the task and every 4000 msec for the textual portion.

Figure 2. Cyber Defense Task

2.2.3.1 Vigilance tasks are very sensitive

Participants were run in a room isolated from any noise and participants were required to wear ear plugs. Light levels were maintained to be consistent throughout the experiment and glare from the lights onto the task screen was minimized as much as possible. Participants were kept away from any possible distractions including being able to see the experimenters. In this study, a half wall was used to isolate the participant from the experimenter. The experimenters were able to see the participant and what they were doing but the participant was not able to see the experimenters.

2.3   Procedures

No study specific procedures were performed without a written and signed informed consent document. After the participant was consented and registered into the study, training on the vigilance task began. Participants received a verbal briefing and PowerPoint presentation that described the vigilance task followed by two 5-minute practice sessions. Also during this time the participant was to complete a personality and brief demographic questionnaire. Participants then donned the eye-tracker and completed the 40-minute vigilance task. Afterwards, the participants were finished for that day and returned to their normal duties. Each participant completed four data collection sessions. Each data session occurred on a separate day. During each data collection session, they repeated the procedures of the initial session except for the personality inventory and training sessions.

2.4   Data Analysis

Upon completion of testing, oculometric data and vigilance task metrics were averaged in 10-min increments (10, 20, 30, 40 min) and used as dependent variables in univariate repeated-measures analyses of variance (ANOVAs). The performance data from the dual task was averaged together to give a total score for each time epoch. Factors were Day (1 – 4) and Time (10, 20, 30, 40 min). Statistical significance tests were based on an alpha level of .05. Some participants had a day of performance data that was not usable due to incorrect data recording. As a result, a participant's data was not included in analysis unless there were at least three sessions (days) of usable data. Proc Mixed in SAS was used to perform the repeated-measures ANOVAs. This procedure uses maximum likelihood to estimate covariances within a subject and then uses these covariance estimates to estimate coefficients for fixed effects. Satterthwaite-type degrees of freedom were used for all F-tests (SAS Version 9.2). Least squares means (LSMeans) are means adjusted for missing data and were used since there were some instances where the eye-tracker lost the pupil during data collection.

Next, each participant's days were categorized as either a Decrement or No Decrement day depending on the percent hits performance. If the linear best-fit slope on a participant's percent hits across the four temporal epochs on a given day was negative, the data day was considered as a Decrement. Positive slopes or zero $\pm$ 0.1 slopes were considered a No Decrement day. For each participant, variables were averaged across days at each time point, separately for Decrement and No Decrement days. Pearson partial correlations controlling for subject (same as ANOCOV with subject as a factor) were performed separately for Decrement and No Decrement days to relate percent hits performance to the six oculometrics.

Personality trait variables from the Big Five (Neuroticism, Extraversion, Openness to Experience, Agreeableness, and Conscientiousness) were averaged across participants and correlated (using Pearson's correlation coefficient) with data on gender, age, rank/academic status, career field, and the number of days in which a vigilance decrement was recorded for each subject (anywhere from zero in which no decrements were observed, to a maximum of four days in which a decrement was recorded on all test days). Correlations were tested for statistical significance by applying a two-tailed t-test using a significance level of 0.05.

3.0 RESULTS

Results are presented in three different sections. First, we present the results for the Day and Time ANOVAs. Next, we present the correlations of the 12 variables in relation to percent hits. Finally, we present the results for the analysis of the personality inventory and demographics information collected. All results included all 20 participants except for personality and demographics, which will be explained in detail in that section.

3.1 Analysis for Day and Time

The repeated measures ANOVA results with factors Day (1, 2, 3, 4) and Time (10, 20, 30, 40 min) are displayed in Table 1 below. Significant F-tests have the p-value cell grayed. ANOVAs were used to compare days and times for each of the variables. Table 2 displays the LSMeans for each day and time point as well as the approximate standard error of the mean (SEM).

Table 1. ANOVA Results for Day and Time

Dependent Variable	Day				Time				Day*Time			
	DF	DFe	F	p	DF	DFe	F	p	DF	DFe	F	p
Percent Hits (graph)	3	55.0	6.58	0.0007	3	219.0	2.51	0.0593	9	219.0	0.84	0.5793
Percent Hits (text)	3	56.2	2.09	0.1122	3	55.3	0.64	0.5933	9	166.2	0.64	0.7651
Left Blink Frequency (blpm)	3	55.9	0.42	0.7390	3	57.4	9.31	0.0001	9	169.3	1.87	0.0596
Right Blink Frequency (blpm)	3	56.1	0.93	0.4321	3	57.4	6.34	0.0009	9	168.9	3.33	0.0009
Left Blink Duration (ms)	3	56.0	2.09	0.1112	3	57.1	29.59	0.0001	9	169.0	1.06	0.3944
Right Blink Duration (ms)	3	56.1	1.81	0.1565	3	57.5	25.88	0.0001	9	169.3	2.33	0.0168
Left PERCLOS	3	56.1	0.33	0.8005	3	57.4	18.95	0.0001	9	169.7	1.64	0.1070
Right PERCLOS	3	56.1	0.62	0.6030	3	57.5	13.70	0.0001	9	169.3	1.80	0.0706
Left Pupil Diameter (mm)	3	56.0	4.60	0.0060	3	57.6	27.78	0.0001	9	169.4	1.77	0.0780
Right Pupil Diameter (mm)	3	56.1	1.08	0.3666	3	56.1	47.84	0.0001	9	167.9	2.64	0.0070
Left Pupil Eccentricity	3	56.0	0.64	0.5942	3	56.9	13.95	0.0001	9	168.6	0.74	0.6755
Right Pupil Eccentricity	3	56.1	1.88	0.1432	3	56.8	10.76	0.0001	9	168.4	0.67	0.7364
Left Pupil Velocity (deg/s)	3	56.0	2.73	0.0527	3	57.5	44.80	0.0001	9	169.7	0.78	0.6307
Right Pupil Velocity (deg/s)	3	56.0	2.16	0.1029	3	57.3	45.30	0.0001	9	169.3	0.84	0.5843

Table 2. LSMeans for each Day and Time. SEM is approximate standard error for each LSMean

Dependent Variable	Day	Time (min)				SEM
		10	20	30	40	
Percent Hits (graph)	1	91.8	94.2	91.8	90.4	1.6
	2	95.6	93.8	93.5	93.3	
	3	97.1	96.4	97.8	96.4	
	4	99.4	97.7	97.4	93.8	
Percent Hits (text)	1	84.9	86.1	83.6	85.8	3.3
	2	92.0	91.8	92.5	95.0	
	3	94.4	94.1	94.4	93.7	
	4	92.8	93.8	88.9	90.9	
Left Blink Frequency (blpm)	1	16.3	17.9	19.9	20.4	2.7
	2	16.6	19.3	22.2	23.8	
	3	17.0	18.2	18.9	20.0	
	4	18.5	17.0	18.0	20.8	
Right Blink Frequency (blpm)	1	14.6	16.6	18.0	20.1	2.7
	2	15.0	16.6	20.3	21.9	
	3	17.9	20.0	20.4	21.1	
	4	16.5	16.0	15.8	16.8	
Left Blink Duration (ms)	1	191.2	199.6	210.8	210.3	8.5
	2	195.7	205.7	221.1	223.0	

	3	199.4	213.4	220.3	217.6	
	4	200.7	210.9	217.4	221.8	
Right Blink Duration (ms)	1	188.2	193.9	203.0	204.2	6.0
	2	190.4	197.7	210.9	217.1	
	3	192.7	206.9	209.9	208.7	
	4	195.6	208.1	212.2	211.8	
Left PERCLOS	1	4.29	6.26	7.47	6.56	1.29
	2	3.97	5.37	7.00	7.66	
	3	4.03	5.10	6.02	5.70	
	4	4.46	4.84	5.45	7.00	
Right PERCLOS	1	3.89	5.14	5.79	6.06	1.12
	2	3.36	4.36	5.91	6.60	
	3	4.22	5.54	6.01	5.90	
	4	3.59	4.09	4.20	4.68	
Left Pupil Diameter (mm)	1	8.61	8.32	8.26	8.22	0.13
	2	8.53	8.33	8.30	8.28	
	3	8.37	8.19	8.17	8.19	
	4	8.26	8.08	8.07	8.08	
Right Pupil Diameter (mm)	1	8.63	8.35	8.27	8.24	0.14
	2	8.53	8.23	8.22	8.24	
	3	8.38	8.20	8.17	8.18	
	4	8.44	8.28	8.25	8.23	
Left Pupil Eccentricity	1	0.523	0.540	0.544	0.551	0.015
	2	0.528	0.552	0.554	0.549	
	3	0.525	0.540	0.548	0.549	
	4	0.519	0.533	0.542	0.549	
Right Pupil Eccentricity	1	0.487	0.507	0.511	0.512	0.014
	2	0.488	0.514	0.515	0.508	
	3	0.490	0.506	0.510	0.508	
	4	0.470	0.488	0.496	0.500	
Left Pupil Velocity (deg/s)	1	0.268	0.299	0.336	0.353	0.023
	2	0.282	0.321	0.357	0.386	
	3	0.262	0.294	0.313	0.323	
	4	0.258	0.284	0.316	0.340	
Right Pupil Velocity (deg/s)	1	0.257	0.288	0.326	0.347	0.022
	2	0.270	0.307	0.340	0.371	
	3	0.252	0.283	0.304	0.313	
	4	0.250	0.276	0.309	0.331	

The Day of data collection had a significant effect on Percent Hits for the graphical portion of the task as well as Left Pupil Diameter (Table 1). Percent Hits increased as the participation day progressed (Figure 3). Left Pupil Diameter was also statistically significant for the effect of Day (Figure 4). On Day 1 average diameter was 8.35 mm (SEM = 0.12) and Day 4 the average diameter for the left eye was 8.12 mm (SEM = 0.12).
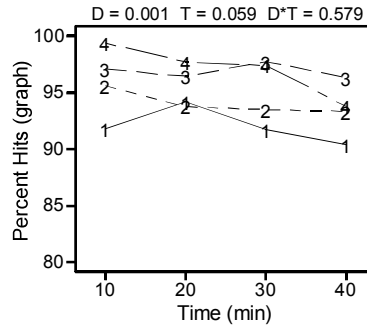
D = 0.001 T = 0.059 D*T = 0.579

Figure 3. Percent Hits Across Time, by Day
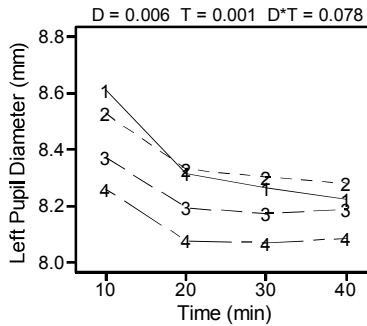
D = 0.006 T = 0.001 D*T = 0.078

Figure 4. Left Eye Pupil Diameter Across Time, by Day

Time on task had a significant effect on Left and Right Blink Frequency, Left and Right Blink Duration, Left and Right PERCLOS, Left and Right Pupil Diameter, Left and Right Pupil Eccentricity, and Left and Right Pupil Velocity. As the Time on task progressed, Left and Right Blink Frequency increased (Figure 5). The LSMean across the four days for the first 10 minutes of the task was 17.1 blinks per minute (SEM = 2.3) in the left eye and 21.3 (SEM = 2.3) blinks per minute for the final 10 minutes of the task. The right eye had similar results with 16.0 blinks per minute (SEM = 2.2) during the first 10 minutes of the task and 20.0 blinks per minute (SEM = 2.2) for the final 10 minutes of the task. This equates to a 25% increase in blinking frequency for the left and right eye.
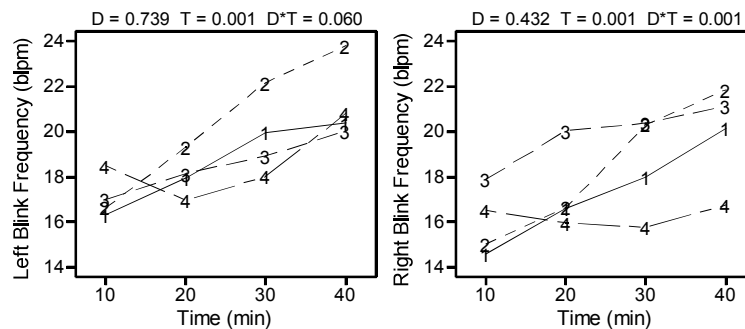
D = 0.739 T = 0.001 D*T = 0.060   D = 0.432 T = 0.001 D*T = 0.001

Figure 5. Left and Right Eye Blink Frequency Across Time, by Day

As Time on task increased from the first 10 minutes of the task to the last 10 minutes of the task, Left and Right Blink Durations became longer (Figure 6). The LSMean for the first 10 minutes of the task across the four days was 196.8 ms (SEM = 7.8) in the left eye and 191.7 ms (SEM =

9

5.1) in the right eye. Whereas, the LSMean for the final 10 minutes of the task was 218.2 ms (SEM = 7.8) in the left eye and 210.4 ms (SEM = 5.1) in the right eye. This equates to 11% longer blink durations in the left eye and 10% longer blink durations in the right eye.
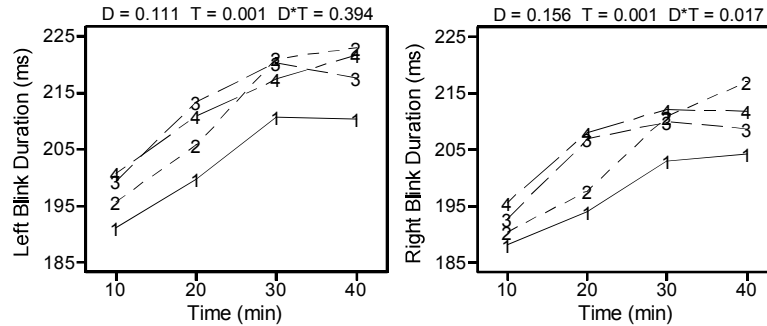

Figure 6. Left and Right Eye Blink Duration Across Time, by Day

Left and Right PERCLOS increased as Time on the task increased (Figure 7). During the first 10 minutes of the task PERCLOS in the left eye had an LSMean across all four days of 4.19% (SEM = 1.04) and 3.76% (SEM = 0.89) in the right eye. During the last 10 minutes of the task the LSMean for the left eye was 6.73% (SEM = 1.04) and 5.81% (SEM = 0.89) in the right eye.
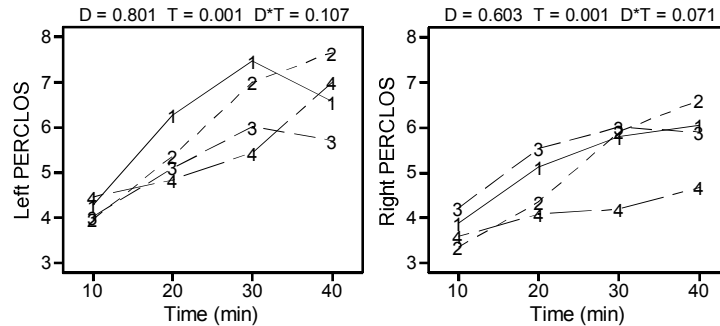

Figure 7. Left and Right Eye PERCLOS Across Time, by Day

Time on task also had a significant effect on Left and Right Pupil Diameter. As Time on the task increased, Pupil Diameter decreased (Figure 8). During the first 10 minutes of the task, the LSMean for Left Pupil Diameter across the four days was 8.44 mm (SEM = 0.12) and Right Pupil Diameter was 8.49 mm (SEM = 0.13). For the last 10 minutes of the task the LSMean for Left Pupil Diameter was 8.20 mm (SEM = 0.13) and Right Pupil Diameter was 8.22 mm (SEM = 0.13). This equates to a 3% decrease in pupil diameter for both eyes.
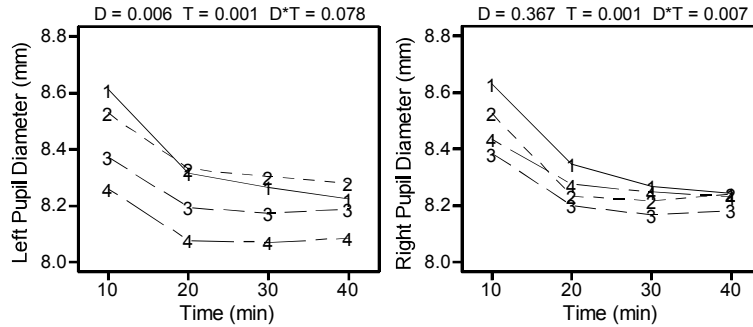
Figure 8. Left and Right Eye Pupil Diameter Across Time, by Day

Left and Right Pupil Eccentricity increased as a function of Time on task increasing (Figure 9). During the first 10 minutes of the task the LSMean across the four days in the Left eye was 0.524 (SEM = 0.014) and the Right eye was 0.484 (SEM = 0.013). During the last 10 minutes of the task the LSMean in the Left eye became 0.549 (SEM = 0.014) across the 4 days and 0.507 (SEM = 0.013) for the Right eye. This equates to a 5% increase in both eyes.
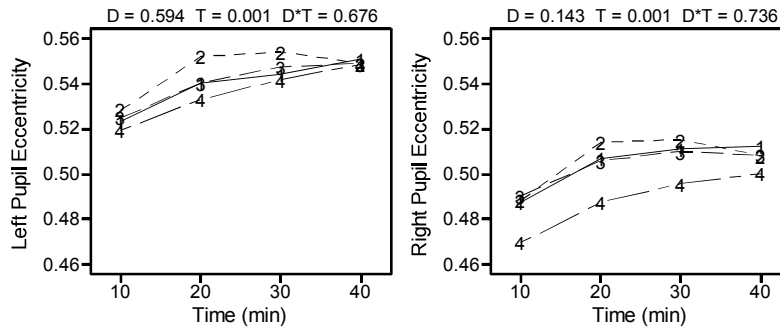

Figure 9. Left and Right Eye Pupil Eccentricity Across Time, by Day

Time on task also had a significant effect on Left and Right Pupil Velocity (Figure 10). Left Pupil Velocity during the first 10 minutes of the task had an LSMean of 0.268 degrees per second (SEM = 0.019) across the 4 days and an LSMean of 0.257 degrees per second (SEM = 0.019) in the Right eye. The LSMean for the last 10 minutes of the task in the Left eye was 0.351 degrees per second (SEM = 0.019) and 0.340 degrees per second (SEM = 0.019) for the Right eye. This equates to a 31% increase in saccadic velocity in the Left eye and a 33% increase in the Right eye.
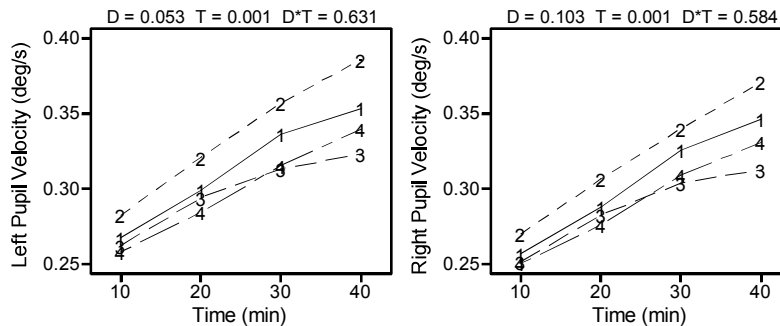

Figure 10. Left and Right Eye Pupil Velocity Across Time, by Day

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An interaction effect for Day and Time was found for Right Blink Frequency, Right Blink Duration, and Right Pupil Diameter.

3.2   Correlations

Pearson partial correlations controlling for subject were performed (separately for Decrement and No Decrement days) to relate Percent Hits to the eye metric variables. Table 3 displays the correlations with their corresponding p-value. Significant partial correlations have their cells grayed. Percent Hits was combined for both tasks to come up with a total percent hits score. If there was a decrease in performance in either task or both tasks that day was considered a decrement day.

Table 3. Pearson Partial Correlations Controlling for Subject

| | Percent Hits | | | |
| | Decrement | | No Decrement | |
Variable Correlated With	r	p	r	p
Left Blink Frequency (blpm)	-0.29	0.0329	0.20	0.1622
Right Blink Frequency (blpm)	-0.20	0.1337	0.28	0.0412
Left Blink Duration (ms)	-0.43	0.0011	0.12	0.4095
Right Blink Duration (ms)	-0.36	0.0064	0.23	0.1026
Left PERCLOS	-0.40	0.0023	-0.07	0.6216
Right PERCLOS	-0.41	0.0021	0.06	0.6482
Left Pupil Diameter (mm)	0.53	0.0001	-0.07	0.6220
Right Pupil Diameter (mm)	0.55	0.0001	-0.14	0.3136
Left Pupil Eccentricity	-0.50	0.0001	0.11	0.4579
Right Pupil Eccentricity	-0.45	0.0005	0.09	0.5128
Left Pupil Velocity (deg/s)	-0.38	0.0037	0.33	0.0186
Right Pupil Velocity (deg/s)	-0.39	0.0033	0.33	0.0175

Left Blink Frequency significantly correlated with Percent Hits in the Decrement group while Right Blink Frequency significantly correlated with Percent Hits in the No Decrement group (Figure 11). As performance decreases in the Decrement group, Left Blink Frequency increases.
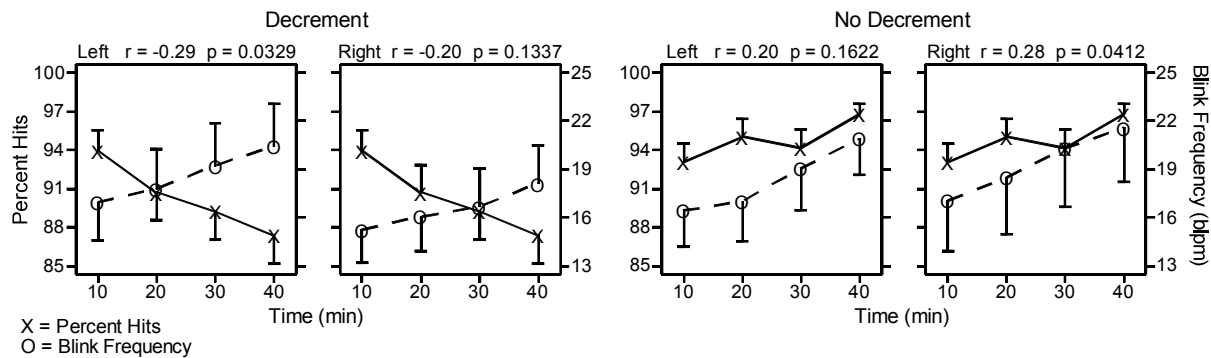

Figure 11. Mean Percent Hits and Left and Right Eye Blink Frequency Across Time, by Day

Left and Right Blink Duration significantly correlated with Percent Hits in the Decrement group (Figure 12). As vigilance performance decreases, Blink Duration increases. There was no significant relationship found for the No Decrement group.

Figure 12. Mean Percent Hits and Left and Right Eye Blink Duration Across Time, by Day

Left and Right PERCLOS significantly correlated with Percent Hits in the Decrement group (Figure 13). PERCLOS increased over time as performance decreased on the task. There was no significant relationship found for the No Decrement group.
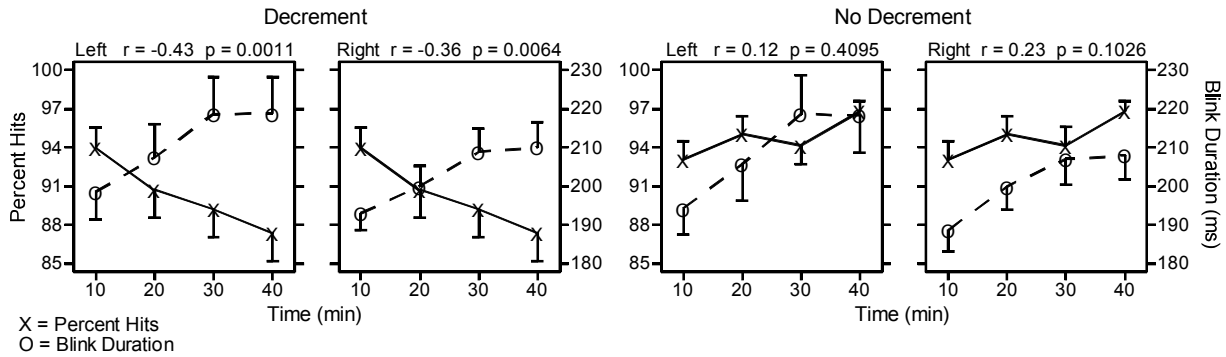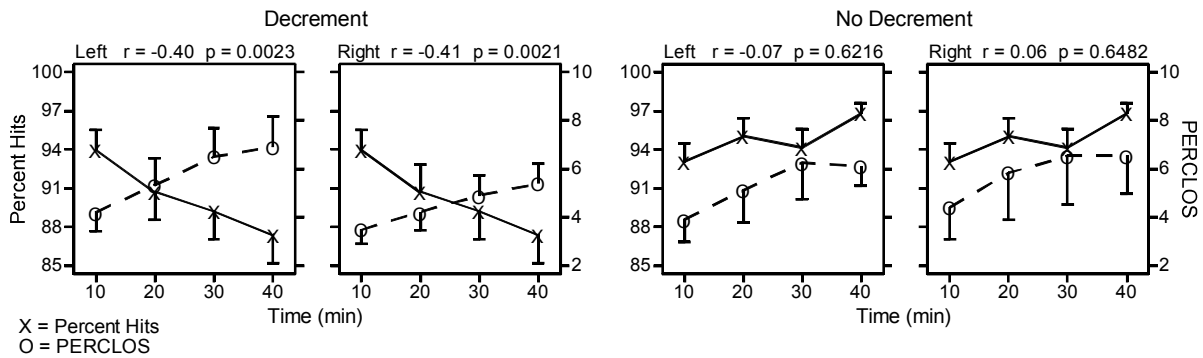

Figure 13. Mean Percent Hits and Left and Right Eye PERCLOS Across Time, by Day

Left and Right Pupil Diameter significantly correlated with Percent Hits in the Decrement group (Figure 14). As performance decreased on the task, Pupil Diameter decreased.
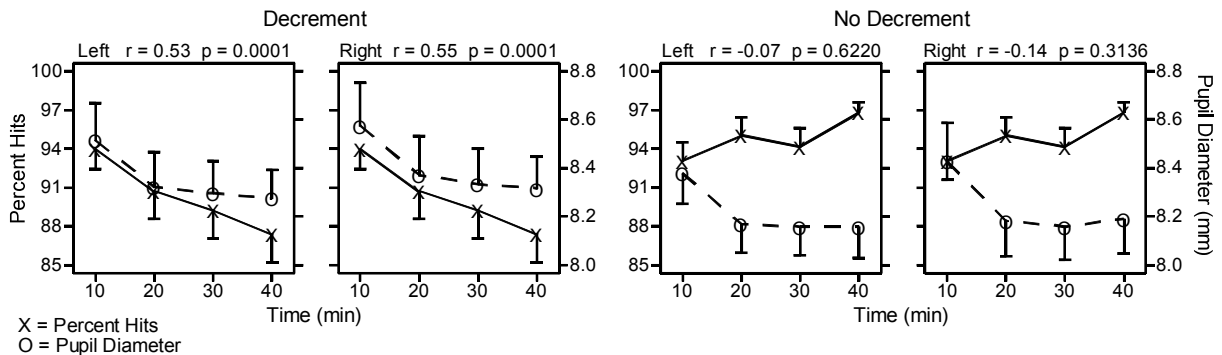

Figure 14. Mean Percent Hits and Left and Right Eye Pupil Diameter Across Time, by Day

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Left and Right Pupil Eccentricity significantly correlated with Percent Hits in the Decrement group (Figure 15). Pupil Eccentricity increased as the detection of critical signals decreased. There was no significant relationship found for the No Decrement group.
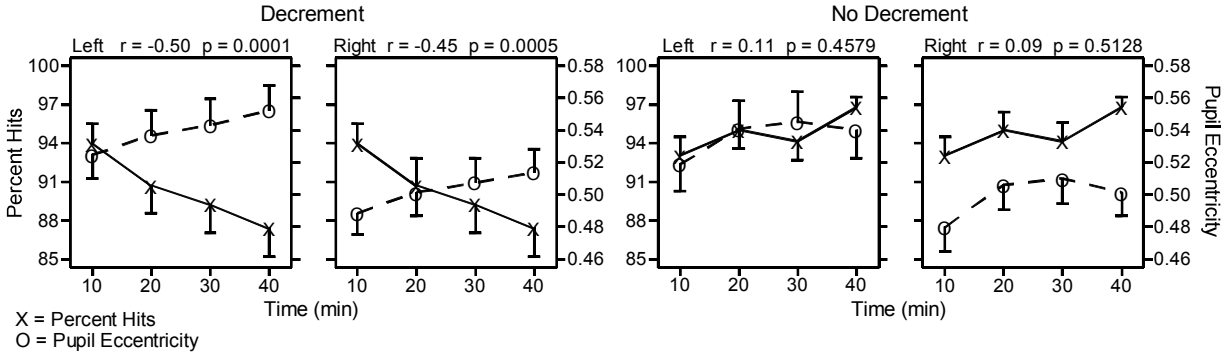

Figure 15. Mean Percent Hits and Left and Right Eye Pupil Eccentricity Across Time, by Day

Left and Right Pupil Velocity significantly correlated with Percent Hits in both the Decrement and No Decrement group (Figure 16). In the Decrement group, Pupil Velocity increases as performance decreases. In the No Decrement group, performance remains fairly stable across time. Pupil Velocity of the participants in this group increases at first before leveling off.
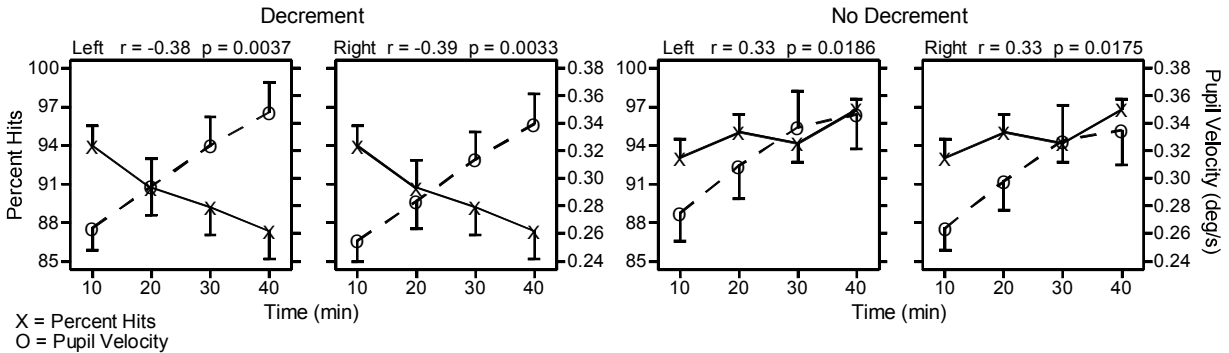
Figure 16. Mean Percent Hits and Left and Right Eye Pupil Velocity Across Time, by Day

3.3 Personality and Demographics

The primary results involving personality and demographics are shown in Tables 3 and 4, respectively. Where possible, we combined our personality and demographic data with the results from a previous related study (McIntire et al., 2011) in which this data was collected along with vigilance performance data. We combined the data due to the difficulty of using small sample sizes (in this study n=20, while in the previous study n=16) to draw clearer inferences about large populations. In this case at least, more data is better data. Next, we present our findings using the Personality Inventory and short demographic questionnaire.

Conscientiousness was the personality factor most strongly related to vigilance performance (the number of days in which a vigilance decrement in performance was observed). Openness to Experience and Agreeableness were also related to vigilance performance. Two personality

factors that were marginally non-significant (but in the suspected causal direction) include Neuroticism and Extraversion.

Table 4. Personality Results (asterisk denotes statistical significance at an alpha level of .05)

Measure	Neuroticism	Extraversion	Openness	Agreeableness	Conscientiousness
Pearson's r	.25	-.25	.30	-.30	-.36
p-value (one tailed)	.071	.071	.038*	.038*	.016*
Sample size	36	36	36	36	36

Table 5. Personality and Demographics (asterisk denotes statistical significance at an alpha level of .05; double asterisks denote significance at an alpha level of .01)

Measure	Age	Gender	Early Bird / Night Owl
Pearson's r	-.35	0.32	0.403
p-value (two tailed)	.036*	.054	.022**
Sample size	36	36	32

For our demographic data results, we found that the age of the participant had a strong correlation with vigilance performance. Essentially, younger persons were more likely to experience the vigilance decrement on any given day relative to older persons (ages ranged from 19 to 41 years with an average age of 27 years, n=36).

We also collected demographic data in which participants self-classified into "Night Owl" types (people who prefer to stay up late and sleep in) versus "Early Birds" (people who prefer to go to bed early and awaken early). We found a very strong relationship between self-classification of Early Birds/Night Owls and the propensity to incur a vigilance decrement on the days of testing. Specifically, we found a significant positive correlation (r = .403, $p[two-tailed]$ = .022) suggesting that Night Owls are much more likely to demonstrate the vigilance decrement than Early Birds.

4.0   DISCUSSION

The discussion section is broken into two separate parts, first the discussion on the eye metrics followed by the personality and demographics discussion.

4.1   Oculometrics

Our results suggest that the six oculometrics examined in our study could be used to monitor vigilance. The oculometrics of blink frequency, blink duration, PERCLOS, pupil diameter, pupil eccentricity, and pupil velocity could be implemented into a monitoring system to measure sustained attention. Such a system could be beneficial in reducing mishaps in many

environments such as air traffic controllers, cyber operators, imagery analysts, unmanned aerial systems operators, and TSA inspectors that are known for the sometimes monotonous aspects of these positions.

The results for blink frequency, blink duration, and PERCLOS found that as attention decreased (performance declined) there was an increase in these oculometrics. This indicates that poor attention to a task could be measured by an increase in blink rate, longer blink durations, and a longer amount of time spent with the eyes closed. We found this same effect in a previous study using a potentially less operationally relevant task (McIntire et al., 2011). The correlations were stronger for the previous study in all eye metrics but we believe this is just a reflection of increased variance moving away from a strictly controlled laboratory task to a more real-world relevant task with more potential sources of variance (McIntire et al., 2011). It is interesting to note that results for this current study indicate that Right Blink Frequency was the only metric to not significantly interact with Percent Hits for the Decrement group but it did for the No Decrement group. In the previous study, our results indicated that performance had a significant effect on blink frequency in the right eye only for the decrement group (McIntire et al., 2011). While no definitive explanation can be offered and because people do not typically blink their eyes independently of one another, we should note our observation that people would completely close one eye and attempt to do the task with just one eye open as the task progressed probably as a countermeasure to fight task-induced fatigue. We should also note that in the decrement group, both eye blink frequency measures were negatively correlated with performance (although only the left eye correlation was statistically significant). The opposite pattern occurred in the no decrement group, in which both eye blink frequency measures were positively correlated with performance (again, only one eye's correlation was significant). These results are suggestive of potentially low statistical power or small effect sizes, which may have been hampered by missing data and by splitting our overall results into two separate analyses (the decrement versus no decrement groupings). Whatever the explanation for these asymmetrical findings across the eyes, more research would be necessary into this particular eye metric before it could be recommended for implementation into a monitoring system.

Others have examined blink frequency and duration during a vigilance task and have consistently found an increase in these metrics as a function of time-on-task (Carpenter, 1984; Funke, 2011; Morris & Miller, 1996; Schroder & Holland, 1968). Similarly, Brookings, Wilson and Swain (1996) found that when participants were paying attention and concentrating on a hard high-workload task their blink rates would decline but when workload levels decreases their blink rates increased. This evidence leads us to believe this metric is still of possible use with more research on more operationally relevant tasks and environments.

On the other hand, PERCLOS appears to be one of the best metrics available for monitoring vigilance according to this study and our previous study (McIntire et al., 2011). Specifically, PERCLOS negatively correlated with performance and appears to mimic the fluctuations in performance for the Decrement group. Other research also indicates that PERCLOS is a useful indicator of performance declines induced by time-on-task fatigue (Dinges & Grace, 1998). Furthermore, studies have also shown that PERCLOS will change in response to changes in cognitive workload (Kawashima, O'Sullivan, & Roland, 1995; Marshall, 2007).

The one oculometric that positively correlated with performance was pupil diameter. Pupil diameter decreased as the number of critical signals detected also decreased. When pupil diameter is small the pupils are said to be miotic. Miosis occurred in our previous study as well as other studies on attention (Lowenstein, Feinberg, & Lowenfeld, 1963; Ludtke, et al., 1998; McIntire et al., 2011). These studies indicate that during miosis a participant's performance is at its worst (Nishiyama et al., 2007; Tsai et al., 2007). Therefore, several previous studies that also found a decrease in pupil diameter suggest that pupil diameter may be an indicator of poor attention (Nishiyama et al., 2007; Warga et al., 2009), which is consistent with our findings from both studies.

As performance on the task decreased an increasing pupil velocity was found. Because our pupil velocity never surpassed 3 degrees per second our observations were classified as microsaccades, as opposed to the larger and more familiar saccades. This is consistent with findings from our previous study (McIntire et al., 2011). We believe our observations are unlikely to be full saccades because the viewing window for the critical signals is so small that full saccades are not necessary to perform well on the task. Saccadic velocity does appear to be related to attention not only through our research but by others as well. Galley (1989) found that tasks requiring high levels of vigilance increased participant's saccadic velocity. In fact, the oculomotor readiness hypothesis states that the movement that controls attention, fixation, and saccades belongs to the same neural circuitry (Rizzolatti, Riggio, Dascola & Umiltá, 1987); therefore, attending to a certain location should result in faster saccades (Hoffman & Subramaniam, 1995). Our results of increasing microsaccades with time-on-task could be indicating that the participant is trying to attend to the task more because they are aware of their decreasing arousal levels. It is important to note that pupil velocity significantly interacted with the No Decrement group as well (although the correlations were in opposite directions across groups). More research is needed into this metric to determine exactly what information it is conveying about behavior.

Pupil eccentricity was found to increase as the number of critical signals detected decreased for the Decrement group. This finding is also concordant with our previous study (McIntire et al., 2011). Pupil eccentricity is increasingly occurring because as closure of the eyes as indicated by blink duration, blink frequency, and PERCLOS increases with time-on-task, the pupils become more occluded by the eyelids causing their shapes to appear more elliptical than round to the eye image analysis software that calculates their shape (Liu, Sun, & Shen, 2010). Furthermore, Lowenstein and Loewenfeld (1962) believe that pupil eccentricity is an indicator of arousal levels. In general, pupillary activity is used in fatigue research as an indicator of arousal levels because pupillary activity is considered the most observable indicator of autonomic nervous system activation (Goldich, Barkana, Pras, Zadok, Hartstein, & Morad, 2010). Therefore, our findings on pupillary activity (pupil diameter, pupil eccentricity, and pupil velocity) coupled with findings from previous research lead us to believe that a good system to monitor sustained attention should include monitoring pupillary activity.

As expected for our experiment, the factor of Time was significant for all oculometrics. As time-on-task progressed blink frequency increased 25%, blink duration increased 38%, PERCLOS increased 58%, pupil diameter decreased 3%, pupil eccentricity increased 5%, and pupil velocity increased 32% for all subjects and sessions (i.e. not broken out into specific groups). These changes indicate that the eyes may reflect the changing attention levels throughout the task. The factor of Day also had a significant effect on Percent Hits for the graphical portion of the task.

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Percent Hits increased as the participation day progressed (Figure 3). In other words, participants got slightly better at detecting the critical signals for this portion of the task with each new day of participation. This is likely to be a training or practice effect that is commonly observed in repeated measures experiments.

4.2   Personality and Demographics

DeVries & Van Heck (2002) found that higher scores on Openness and Neuroticism and lower scores on Extraversion and Conscientiousness were predictive of higher work-related fatigue in non-vigilance settings. And there is compelling previous support for the links between Neuroticism and Extraversion in the fatigue literature (DeVries & Van Heck, 2002). Our statistical results confirmed two of their four findings (regarding Openness and Conscientiousness) but failed to find significant correlations for the other two where the previous literature suggested a link (Neuroticism and Extraversion). It should be noted, however, that the trends for Neuroticism and Extraversion were both in the suspected causal direction and had associated p-values just above the significance level of alpha=.05. DeVries and Van Heck (2002) failed to find an effect of agreeableness on fatigue ratings, but somewhat surprisingly, we found a significant relationship between Agreeableness and vigilance performance. The data show that more agreeable persons (who are relatively more socially compliant, accommodative, cooperative, courteous, helpful, etc.) had better vigilance performance (they were less likely to get the decrement). The explanation may be as simple as this: the participants were simply highly motivated to do what was asked of them by the experimenters, because highly agreeable people are more likely to obey and be polite and helpful and to follow orders. More research on these topics is needed, either to refute or support these findings, and possibly to look further into the sub-facets of the FFM traits (there are six per domain).

For our demographic data results, we found that the age of the participant had a strong correlation with vigilance performance. Essentially, younger persons were more likely to experience the vigilance decrement on any given day relative to older persons. Although previous research has also claimed a relationship between gender and fatigue, specifically with men being more resilient to the effects of fatigue (DeVries & Van Heck, 2002), thus suggesting a possible similar relationship with vigilance, we found no compelling evidence either way although the trend favored women. Admittedly, this finding is just fractionally non-significant potentially due to our sample size being rather small and skewed to over-representation of males with about 20% female volunteers; or 7 female participants in our current combined sample size of 36, so this trend might well disappear with further research.

We also collected some demographic data in which participants self-classified into "Night Owl" types (people who prefer to stay up late and sleep in) versus "Early Birds" (people who prefer to go to bed early and awaken early). We found a very strong relationship between self-classification of Early Birds/Night Owls and the propensity to incur a vigilance decrement on the days of testing. Specifically, we found that Night Owls are much more likely to demonstrate the vigilance decrement than Early Birds. All participants' data collection was done during normal business hours, many of which occurred in the morning hours, which could suggest that Night Owls might not have been fully awake (perhaps near a low point in their circadian cycle). Future research on this topic might find it useful to record time of day of each session, the number of hours of sleep the few days before, sleeping and rising times, subjective ratings of sleep quality,

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etc. It might also be interesting to investigate the extent to which self-classified "Early Birds" are actually able to go to bed late and sleep-in versus their actual sleep times.

5.0   CONCLUSION

Our results indicate that changes in occulometrics correspond to changes in vigilance performance during a cyber operator task. These results are reflective of previous findings using a potentially less operationally relevant task (McIntire et al., 2011). Therefore, it appears that moving toward a more operationally relevant task is possible and that field testing is necessary and possible using this method. Implementation of an eye-tracking device to monitor attention could significantly decrease human error and possibly avoid devastating consequences through the use of perceptual cues or non-invasive brain stimulation techniques to augment human performance. Future research is needed to assess these oculometrics in real-time and to assess their effectiveness in the field.

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